$Z \to b\bar{b}$ in a composite model of fermions

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Abstract

A composite model of fermions is proposed to explain the "anomaly" in $Z \to b\bar{b}$ and, to a lesser extent, in $Z \to c\bar{c}$. It contains a *nonsequential* fourth family whose mass of one member (the charge -1/3 quark) is constrained to be between 47 GeV and 49 GeV. The charge +2/3 quark is constrained to lie between 67 GeV and 107 GeV. This opens up the exciting prospect for near-future discoveries at LEP2 and possibly at the Tevatron.

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I. INTRODUCTION

Precision tests of the Standard Model (SM) have reached a level where it "might" now be possible to look for indirect evidence of new physics and/or new degrees of freedom. One example is the *apparent* discrepancy between theory and experiment in the value of the ratio $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to had)$ [1]. This discrepancy which increases with m_t, reaches the 3 σ level when m_t reaches 175 GeV. In addition the ratio $R_c \equiv \Gamma(Z \to c\bar{c})/\Gamma(Z \to had)$ is 2 σ smaller than the SM prediction. In addition there seems to be some discrepancy between the measurements of the left-right asymmetry A_{LR} done at SLD and at LEP. If one also includes the *apparent* disagreement between the QCD coupling α_S determined at "low" energy and evolved to M_Z with that determined by the Z-lineshape, one is tempted to think that one might be already seeing some new kind of physics. It is therefore very crucial to confirm or disprove these so-called discrepancies. Let us nevertheless assume that they are not mere statistics and examine what kind of new physics that can be possible and what predictions that can be tested in the near future. Even if the discrepancy were to disappear, this would put a severe constraint on this type of new physics.

In this manuscript, a mechanism is proposed to explain the apparent increase of R_b and, as a consequence, the decrease in R_c , and to make further predictions on other branching ratios, and ultimately to constrain the new physics involved in the mechanism itself. It is based on the assumption that there is a new, heavy, *nonsequential* down quark ($Q = -1/3$) (part of a new family) with mass greater than 47 GeV and whose $q\bar{q}$ bound state(s) (by QCD) mixes with the Z boson. By *nonsequential*, we mean that the fermions of the new family has very little mass mixing with fermions of the other three generations. (The description of a concrete model is given below.) Consequently, the following predictions are made for the hadronic widths. We make the following predictions. There is a *decrease* in $R_c \equiv \Gamma(Z \to c\bar{c})/\Gamma(Z \to had)$ and $R_u \equiv \Gamma(Z \to u\bar{u})/\Gamma(Z \to had)$, and an *increase* in $R_d \equiv \Gamma(Z \to d\bar{d})/\Gamma(Z \to had)$, $R_s \equiv \Gamma(Z \to s\bar{s})/\Gamma(Z \to had)$ and $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to had)$, all in comparison with the SM predictions. All of these changes are predicted in terms of a single

increase in $\Gamma(Z \to b\bar{b})$. If the new, heavy vector meson couples universally (with a different strength in principle) to the ordinary leptons then $\Gamma(Z \to \nu\bar{\nu})$ and $\Gamma(Z \to l^+l^-)$ are also predicted to decrease and increase respectively. Our predictions are in basic agreement with all Z-pole observables except for one: the left-right asymmetry A_{LR}. There our prediction is in agreement with the SLD data. This is perhaps also an indication of new physics such as the type discussed in this paper. In this regard, it is important to stress the fact that one has to take into account, in *any* discussion of new physics affecting R_b, other electroweak observables as well, such as A_{LR}, Γ_Z, σ_{had}, etc..., and not just R_b and R_c.

Some comments will be made regarding the possible mass ranges of the new fermions as well as the range of compositeness scales of the model to be described below.

II. A MODEL

In this section we shall describe a model which motivates the subsequent phenomenological discussion. We shall expose mainly the salient features of the model needed for this discussion, leaving out some details for a subsequent paper which will focus on the construction of the model and its implications concerning mass matrices.

The model we are concerned with in this paper is a confining model in the manner of Abbott-Farhi [2], where the usual quarks and leptons are viewed as composites of more fundamental fermions and scalars. In contrast with the Abbott-Farhi model where the confining gauge group is the electroweak group, here it is a *family* gauge group which is confining. Also, in contrast with the composite models constructed long ago by various authors, here W and Z *are* fundamental gauge fields while there exists composite (global) family vector bosons with masses as high as the compositeness scale itself. To summarize, the Abbott-Farhi model contains composite weak vector bosons while the model presented here contains composite horizontal or family vector bosons. The reason for considering this kind of model is a desire to understand the family structure of the standard model and its mass matrices.

The model is a Left-Right symmetric extension of the Standard Model with a confining Left-Right horizontal gauge group. The gauge structure is $\{SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}\} \otimes SU(2)_{HL} \otimes SU(2)_{HR}$, with $SU(3)$ being the usual color gauge group.

Let us recall that in Abbott-Farhi-type models, the scalar sector has an additional global $SU(2)$ and it was this $SU(2)$ that acted as an effective weak interaction group. Let us also recall that there the preonic fermions and scalars transform as singlets and doublets under that global symmetry respectively. (As a result, quarks and leptons which are fermion-scalar bound states and W and Z which are scalar-scalar bound states transform as doublets and triplets under the global $SU(2)$ symmetry respectively.) What are the differences between the present model and the Abbott-Farhi one?

Here the additional global symmetries will be $SU(2)_{GL} \otimes SU(2)_{GR}$ in analogy with the Abbott-Farhi model, with the *difference* being that these global symmetries are now attached to *horizontal* left and right symmetries. The minimal preonic particle content is given by: $\Psi_{qL} = (3, 2, 1, 2, 1, 2, 1, 1/3)$; $\Psi_{qR} = (3, 1, 2, 1, 2, 1, 2, 1/3)$; $\Psi_{lL} = (1, 2, 1, 2, 1, 2, 1, -1)$; $\Psi_{lR} = (1, 1, 2, 1, 2, 1, 2, -1)$; $\phi_L = (1, 1, 1, 2, 1, 2, 1, 0)$; $\phi_R = (1, 1, 1, 1, 2, 1, 2, 0)$, where Ψ and ϕ denote fermions and scalars respectively. The transformations are with respect to $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes SU(2)_{HL} \otimes SU(2)_{HR} \otimes SU(2)_{GL} \otimes SU(2)_{GR} \otimes U(1)_{B-L}$. Notice that in our minimal model the scalar fields are singlets with respect to the electroweak group.

Let us assume that $SU(2)_{HL} \otimes SU(2)_{HR}$ is confining. The physical quarks and leptons, which are now composite objects, transform as: $q_L = (\Psi_{qL}\phi_L) = (3, 2, 1, 1, 1, 1 + 3, 1, 1/3)$; $q_R = (\Psi_{qR}\phi_R) = (3, 1, 2, 1, 1, 1, 1 + 3, 1, 1/3)$; $l_L = (\Psi_{lL}\phi_L) = (1, 2, 1, 1, 1, 1 + 3, 1, -1)$; $l_R = (\Psi_{lR}\phi_R) = (1, 1, 2, 1, 1, 1, 1 + 3, -1)$. Notice that under the global horizontal (family) group $SU(2)_{GL} \otimes SU(2)_{GR}$, the left and right-handed quarks and leptons transform as a triplet plus a singlet, i.e. there are four families in this model, with the fourth one (singlet) being separate from the other three in the lowest order. This is the statement made in the introduction.

A remark is in order here. If the preonic quarks and leptons were to transform as singlets under the global horizontal group, there would only be two families of *composite* quarks and leptons. To incorporate the third family, one would have to add another set of preons with

the result that one now has two sets of disjointed double families. This does not appear to be the case in reality and, in any case, one also ends up with four families. The previous scenario of three connected families and one disjointed family (in the lowest order) seems to be more desirable.

We would like to make one more remark. Another possible scenario not considered here is to keep $SU(2)_{HL} \otimes SU(2)_{HR}$ unconfined and to endow the preonic fermions and scalars with some extra confining gauge symmetry and that they transform as fundamentals under that extra gauge symmetry. Again, the (fermion- scalar) composites would decompose into triplets and singlets of the (now gauged) horizontal symmetry.

The moral of the story is that as long as the (gauge or global) horizontal symmetry is $SU(2)$ and that the *preonic* fields are doublets, one would get three connected families (the standard three families) and one disconnected one (in the lowest order) at the composite level. Let us denote this *nonsequential* family by $Q = (\mathcal{R}, \mathcal{P})$ for the quarks and by $L = (\mathcal{N}, \mathcal{E})$ for the leptons. This nonsequential family behaves *exactly* like the standard three families under the gauge group $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$. We would like to stress this point in order to avoid any misunderstanding: the nonsequential family is just another generation which is disconnected from the other three (in the lowest order).

Below the scale of "compositeness", there can be, besides the usual gauge interactions among the composite fermions, several four-fermi interactions, some of which are relevant for the present discussion and some for the study of mass matrices. (They can be viewed as resulting from the exchange of some composite bosons.) We are mainly concerned here with the interactions between the nonsequential fourth generation and the other three. This is because we are interested in the effects of the nonsequential generation on physics involving ordinary quarks and leptons. To this end, let us denote $G_{gauge} = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ and $G_{global} = SU(2)_{GL} \otimes SU(2)_{GR}$. The interactions should be invariant under G_{gauge} but not necessarily under G_{global} which could be broken explicitly by these interactions. Let us recall that the nonsequential fourth generation is singlet under G_{global}.

There are several scenarios. We shall present one of such scenarios here. Let us assume

for example that there is a neutral interaction between the nonsequential fourth generation and the other three of the form which is G_{global}-invariant, namely

$$\mathcal{L}_{q0} = (g_q^2/\Lambda^2) \sum_i \bar{\mathcal{Q}}_i \gamma_\mu \mathcal{Q}_i \sum_j \bar{q}_j \gamma^\mu (1 - \gamma_5) q_j, \tag{1}$$

where the sums over i and j refer to all quarks of the new and "old" generations respectively. $\mathcal{L}_{q0}$ will provide the kind of coupling which is used here and whose phenomenological implications concerning $Z \to b\bar{b}$ are discussed below. In addition, we could have the following interactions among the "new" quarks and the "old" leptons:

$$\mathcal{L}_{l0} = (g_l^2/\Lambda^2) \sum_i \bar{\mathcal{Q}}_i \gamma_\mu \mathcal{Q}_i \sum_j \bar{l}_j \gamma^\mu (1 - \gamma_5) l_j, \tag{2}$$

where, in principle, $g_l \neq g_q$. These two equations represent the relevant interactions for describing the phenomenology of the new, heavy quark bound state mentioned earlier and to which we shall come back below. We then discuss the limitation of these assumptions and suggest possible modifications.

In addition we shall assume the following G_{global} breaking term:

$$\mathcal{L}_B = (g_b^2/\Lambda^2)(\bar{\mathcal{Q}}\Gamma\frac{\vec{\tau}}{2}\mathcal{Q} + \bar{\mathcal{L}}\Gamma\frac{\vec{\tau}}{2}\mathcal{L}) \cdot \bar{l}_3 \Gamma\frac{\vec{\tau}}{2} l_3, \tag{3}$$

where $l_3 = (\nu_\tau, \tau)$, and $\Gamma = 1, \gamma_\mu(1 - \gamma_5), (1 - \gamma_5)$, etc.... $\mathcal{L}_B$ is G_{global}- breaking because only l_3 is present. At present, we have not explored the possible sources for this term. One possibility would be the mixing of the "charged Higgs" coupled to the nonsequential family with the corresponding one which couples to the standard families. (In our scenario, it is unavoidable to have several physical scalars.) Since the "standard family" charged Higgs will couple preferentially to $\tau\nu$ as far as the lepton sector is concerned, it might be possible that the couplings and masses (of the mixed one) are such as to favor $\mathcal{R} \to \mathcal{P}\tau^+\nu$. It will be seen at the end of the paper that this kind of interaction which provides a non-standard decay mode for the $\mathcal{R}$ quark is severely constrained by CDF and D0. Another remark is in order here. The Λ's in $\mathcal{L}_{q0}$ and $\mathcal{L}_B$ are not necessarily the same. For simplicity we shall take them to be equal to each other, keeping in mind that they can differ in value.

$\mathcal{L}_{q0,l0}$ will form the backbone of the phenomenology of this paper while $\mathcal{L}_B$ will be seen to provide the dominant leptonic decay mode of the fourth generation provided g_b^2/Λ^2 is large enough which we will see to be the case. This will provide the rationale for its unobservability at the present time because the leptonic decay of $\mathcal{R}$ will be mostly into $\mathcal{P}\tau\nu$. We shall come back to this point below.

One last remark is in order. In general, one expects all kinds of four-fermi interactions, including two classes which are not directly relevant to the present discussion. One of such classes is the four-fermi interactions involving only the fourth generation. For obvious reasons we are not interested in such a class in this paper. The other one is the four-fermi interactions involving only fermions of the first three generations. These are the kind of interactions that we shall use to construct mass matrices in a separate paper. The nature of these interactions, including the coefficients g_i^2/Λ_i^2 in front, is however unknown. Each assumption concerning one of these interactions will have some phenomenological consequences which results in the experimental constraints on g_i^2/Λ_i^2 which are *not necessarily* the same as those given in Eq. (1, 3). To be more complete here we shall write down a generic term of the form

$$\mathcal{L}_f = (g_i^2/\Lambda_i^2)\bar{f}_1\Gamma f_2\bar{f}_3\Gamma' f_4, \tag{4}$$

where f denotes some generic third-generation fermion, Γ denotes some generic Lorentz and internal symmetry structure, and the subscript i labels the coefficients which appear in front of these interactions.

We shall now come to the main part of this paper, namely the effect of the nonsequential fourth generation, specifically the quarks, on the decay of the Z boson.

III. PHENOMENOLOGICAL ANALYSIS OF $Z \to b\bar{b}$

Although the discussion presented below concerning the decay mode $Z \to b\bar{b}$ is related to our composite model, we shall present it in a way which is general enough to be applicable to other models as well. The only assumption is the existence of nonsequential fourth family with a particular coupling to the other three families.

Before we start the discussion on the effects of this nonsequential fourth family on $Z \to b\bar{b}$, a few remarks are in order concerning a potential mixing between the SM Z boson and Z' coming from $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$. How big or how small such a mixing is depends on the details of the Higgs sector. We shall *assume* that such a mixing, if it exists, is small enough as to give a negligible contribution to $Z \to b\bar{b}$ and other observables. In fact, an analysis of precision electroweak data as applied to extended gauge models, in particular a Left-Right model as used in this paper, by Ref. [3,4] constrained the mixing to be very small. By parametrizing the mixing in terms of an angle ξ, namely $Z = cos\xi Z_S + sin\xi Z_N$ and $Z' = -sin\xi Z_S + cos\xi Z_N$, where Z_S and Z_N are the SM and new gauge bosons before mixing, the authors of Ref. [3,4] found that ξ is constrained by precision electroweak data to be less than 1 %. The reader is referred to Ref. [3,4] for more details.

From hereon we shall assume that the mixing with Z' is *negligible*. The mixing is assumed to be negligible both at the tree level and even at the one-loop level (through the top quark for example) if Z' is heavy enough. Although the possibility of various deviations which might come from the mixing with Z' is interesting in its own right, we would like to present yet another mechanism for such a deviation and choose to neglect the effect of Z' if the mixing is assumed to be very small. We shall therefore concentrate on the effects of the mixing between Z and a heavy quarkonium.

As we have mentioned above, let us denote this *nonsequential* family by $(\mathcal{R}, \mathcal{P})$ for the quarks and by $(\mathcal{N}, \mathcal{E})$ for the leptons. For reasons to be given below let us assume that the $(Q = -1/3)$ quark has a mass $m_{\mathcal{P}} < m_{\mathcal{R}}$. We also assume that the up-type quark $\mathcal{R}$ is heavy enough so that $\mathcal{R}\bar{\mathcal{R}}$ QCD bound states are well above the $\mathcal{P}\bar{\mathcal{P}}$ open threshold. The $\mathcal{P}\bar{\mathcal{P}}$ QCD bound states can be described by Richardson's potential. Such an analysis has been carried out long ago by [5] for the $^3S_1$ $t\bar{t}$ bound states, but unfortunately in the now-obsolete range of $m_t \sim 40 - 50$ GeV. This analysis can however be applied to any quark in a similar mass range or higher, especially for our case where $m_{\mathcal{P}} > 46$ GeV. (The mass shift of the Z boson due to this mixing is negligible [5].)

$\mathcal{P}\bar{\mathcal{P}}$ QCD bound states which can mix with Z are either vector, axial vector, or both.

In what follows we shall neglect the mixing of Z with the axial vector states since it goes like β^3 [6,5]. Consequently we shall focus only on the vector meson ($^3S_1$) bound states. In particular, we shall first examine the mixing of the ground state $1S$ with Z. In the mass range considered here, the ground state $1S$ is sufficiently far from open-$\mathcal{P}$ threshold so that the mass-mixing formalism can be applied. Denoting the $1S$ ($J^{PC} = 1^{--}$) state by V^0, the result of V^0 and Z^0 mixing is given in terms of the mass eigenstates [5]

$$|V\rangle = cos\frac{\theta}{2}|V_0\rangle - sin\frac{\theta}{2}|Z_0\rangle, \tag{5a}$$

$$|Z\rangle = sin\frac{\theta}{2}|V_0\rangle + cos\frac{\theta}{2}|Z_0\rangle, \tag{5b}$$

for the mass eigenvectors and where

$$\theta = sin^{-1}(\delta m^2/\Delta^2), \tag{6}$$

with

$$\Delta^2 = [\frac{(M_{V_0}^2 - i\Gamma_{V_0}M_{V_0} - M_{Z_0}^2 + i\Gamma_{Z_0}M_{Z_0})^2}{4} + (\delta m^2)^2]^{1/2}. \tag{7}$$

δm^2 is the off-diagonal element of the mass mixing matrix and is given by [5]

$$\delta m^2 = F_V[(\frac{g}{cos\theta_W})\frac{\frac{4}{3}sin^2\theta_W - 1}{4}], \tag{8}$$

where

$$F_V = 2\sqrt{3}|\Psi(0)|\sqrt{M_{V_0}}. \tag{9}$$

and where the factor 3 comes from the number of colors and $|\Psi(0)|$ is the wave function at the origin which can be computed using the Richardson's potential in QCD. The term inside the square brackets represents the *vector* coupling of the $\mathcal{P}$ quark to the Z boson.

Let us assume that $M_V > M_Z$ and since present experiments are carried out on the Z resonance, we need only to look at Eq. (5b) to see how the presence of V_0 modifies the coupling of Z to "light" quarks and leptons. This, as we claim in this manuscript, is a

possible source for the discrepancy seen in $\Gamma(b\bar{b})$. From Eq. (5b), one finds the physical Z couplings to a given fermion f to be

$$g_{Zf\bar{f}}^{V,A} = sin\frac{\theta}{2}g_{V_0f\bar{f}}^{V,A} + cos\frac{\theta}{2}g_{Z_0f\bar{f}}^{V,A}, \tag{10}$$

where V and A stand for vector and axial-vector couplings respectively. $g_{V_0f\bar{f}}^{V,A}$ and $g_{Z_0f\bar{f}}^{V,A}$ are the couplings before mixing.

Before mixing, the heavy quarkonium V_0 can decay into $f\bar{f}$ via γ if there were no new physics involved. (The reader is referred to Ref. [7] for a pedagogical discussion of this point.) This source alone however gives only a small change to R_b. A new and unconventional coupling of $\mathcal{P}$ to b (and to other normal fermions as well) is needed to bring R_b closer to its experimental value. We have seen in the previous section how such coupling can arise in our composite model. Let us write

$$g_{V_0q\bar{q}}^{V,A} = F_V G_q^{V,A}(s = M_Z^2) + g_{new,q}^{V,A}, \tag{11}$$

where $G_q^{V,A}$ can be found in [7].

$$G_q^V(M_Z^2) = e^2\frac{Q_qQ_\mathcal{P}}{M_Z^2} \tag{12a}$$

$$G_q^A(M_Z^2) = 0 \tag{12b}$$

and where Q_q and $Q_\mathcal{P}(= -1/3)$ are the electric charges. $g_{new,q}^{V,A}$ is the coupling of V_0 to a quark q and is found to arise from $\mathcal{L}_0$ as we shall see below. We would like to constrain $g_{new,q}^{V,A}$ using the experimental value of R_b. A similar term can be written for the coupling of V_0 to a lepton l where one now has Q_l and $g_{new,l}$.

For the mass range considered below , namely $m_\mathcal{P} > 46GeV$, $|\Psi(0)|$ is such that [5] $|\delta m^2| \ll |M_{V_0}^2 - i\Gamma_{V_0}M_{V_0} - M_{Z_0}^2 + i\Gamma_{Z_0}M_{Z_0})^2|/2$ and consequently

$$sin\frac{\theta}{2} \approx \frac{\delta m^2}{M_{V_0}^2 - M_{Z_0}^2 + i(\Gamma_{Z_0}M_{Z_0} - \Gamma_{V_0}M_{V_0})}, \tag{13}$$

with $cos\frac{\theta}{2} \approx 1$. Typically, $\theta/2 \approx 2 - 3 \times 10^{-2}$ and the deviation of $cos\frac{\theta}{2}$ from unity will be of order 10^{-4} and can be neglected considering the present level of precision.

The modified couplings of Z to a quark q are now

$$\tilde{g}_q^V = (1 + \eta_{q,W}^V + \eta_{q,new}^V)g_q^V, \tag{14a}$$

$$\tilde{g}_q^A = (1 + \eta_{q,new}^A)g_q^A, \tag{14b}$$

where W stands for electroweak and the η's are complex numbers and are defined by

$$\eta_{q,W}^{V,A} = sin\frac{\theta}{2}F_V G_q^{V,A}(s = M_Z^2)/g_q^{V,A}, \tag{15a}$$

$$\eta_{q,new}^{V,A} = sin\frac{\theta}{2}g_{new,q}^{V,A}/g_q^{V,A}, \tag{15b}$$

where the explicit forms for $\eta_{q,W}^V$ and $\eta_{q,new}^{V,A}$ can be obtained by using Eqs. (11,13). *For simplicity*, we shall assume the new interactions to be V-A, namely $g_{new,q}^V = -g_{new,q}^A = g_{new,q}$. This is consistent with $\mathcal{L}_{q0}$ in Eq. (1). There the V-A nature of the "standard" quark (denoted by q) current was explicitly assumed. We shall try to relate $g_{new,q}$ to the compositeness scale below. Let us however be slightly more general and take $g_{new,q}$, for the moment, to simply parametrize the "new physics" involved in $Z \to b\bar{b}$ and extract it from R_b.

The modified coupling of Z to a lepton l can be written in a similar fashion to Eqs. (14a, 14b) with the substitution $q \leftrightarrow l$. In terms of the new physics, we now have two parameters: $g_{new,q}$ and $g_{new,l}$. In principle, they can be very different from each other.

In computing the Z widths using Eqs. (14a,14b) and the range of mass mentioned earlier, one can safely *neglect* terms proportional to $(Re\,\eta)^2$ and $(Im\,\eta)^2$ since they turn out to be *at least* two orders of magnitude smaller than terms proportional to $Re\,\eta$ (assuming $g_{new,f}^V < 1$). (Considering the present level of precision, their inclusion is irrelevant to the present discussion.) With this remark in mind, the decay width for $Z \to f\bar{f}$ is now given by

$$\Gamma(Z \to f\bar{f}) = \Gamma_f^{SM}(1 + \delta_{new}^f), \tag{16}$$

where $f = q, l$ and where

$$\delta_{new}^f = \frac{2(g_f^V)^2(Re\,\eta_W^V + Re\,\eta_{new}^V) + (g_f^A)^2\,Re\,\eta_{new}^A}{(g_f^V)^2 + (g_f^A)^2}. \tag{17}$$

In Eq. (16), Γ_f^{SM} contains various radiative correction factors as well as mass factors such as defined in Ref. ([8]). We find

$$\Gamma(had) = \Gamma^{SM}(had) + \delta_{new}^u(\Gamma_u^{SM} + \Gamma_c^{SM})$$
$$+ \delta_{new}^d(\Gamma_d^{SM} + \Gamma_s^{SM} + \Gamma_b^{SM}), \tag{18a}$$

$$R_f = \frac{R_f^{SM}(1 + \delta_{new}^f)}{1 + \delta_{new}^u(R_u^{SM} + R_c^{SM}) + \delta_{new}^d(R_d^{SM} + R_s^{SM} + R_b^{SM})}, \tag{18b}$$

where $R_f \equiv \Gamma(Z \to q_f \bar{q}_f)/\Gamma(had)$. The central theme of this paper is the use of R_b to obtain information on the model proposed here. By using Eq. (18b) for R_b, one can extract the parameters $Re\eta_{b,new}^{V,A}$ and consequently the *common* parameter $sin\frac{\theta}{2}g_{new}$ as a function of M_{V_0}. This will then be used to make predictions on various ratios mentioned above and also on the total Z width. Finally $Re\eta_{new}^{V,A}$ will also give information on the possible values for $g_{new,q}$ and consequently on the scales of new physics as we shall see below.

We shall use the following experimental ratio [1]: $R_b = 0.2219 \pm 0.0017$. In our analysis, the SM predictions as functions of the top quark and Higgs masses (see e.g. [8]) are listed in Table 1. (Notice that the results of [8] are obtained for $\alpha_S(M_Z) = 0.12 \pm 0.01$).

Our strategy is to extract $g_{new,q}$ from R_b and to use it to make predictions on R_c and R_s (R_u and R_d are practically the same as these two respectively). They are listed in Table 2. To make predictions concerning the leptonic sector, one has to know $g_{new,l}$. This can be done by choosing values that fit $R_e \equiv \Gamma(had)/\Gamma(e\bar{e})$ and, consequently, use them to predict A_{LR}, σ_{had}, and Γ_Z. This is the procedure we choose to follow in this paper. The results are listed in Table 3 along with the respective experimental values. Let us now discuss these results.

A look at Table 2 shows that our predictions for R_c are in basic agreement with the experimental value. The basic observation here is there is a *decrease* in R_c with respect to the SM prediction which is shown in Table 1. In our model this decrease is *real* and is due to an increase in R_b. The amount of the decrease in R_c, for a given top quark mass, is entirely *determined* by the amount of increase in R_b. This prediction is fixed in our model.

We also predict an increase in $R_s = R_d$, and a decrease in $R_u = R_c$. The results are shown in Table 2. These predictions are insensitive to the Higgs mass.

Notice that an increase in the ratio for a down-type quark corresponds to a decrease in the ratio for an up-type quark and vice versa. This happens because $Re\eta_{f,new}^{V,A}$ is positive for $f = u, c$ and negative for $f = d, s, b$. (V_0 is a $\mathcal{P}\bar{\mathcal{P}}$ bound state.) Also notice that, in terms of the experimental R_b, one can also write $R_{c,s} = (\Gamma_{c,s,u}^{SM}/\Gamma_b^{SM})((1 + \delta_{new}^{c,s})/(1 + \delta_{new}^b))R_b$. It turns out that $(1 + \delta_{new}^{c,s})/(1 + \delta_{new}^b)$, and hence $R_{c,s}$, is independent of M_V.

Beside R_b and R_c, can the presence of V and its mixing with Z affect other observables such the Z-width, σ_{had}, and asymmetries such as A_{LR}? In particular, will these observables deviate significantly from their standard model predictions and hence signal the presence of V even if one is a few V-width away from its peak? These are the questions which we will address below.

As we have discussed above, the prediction on the hadronic branching ratios, R_c, etc..., can be made once we extract $g_{new,q}$ from R_b. (The actual values of $g_{new,q}$ will be given below in the discussion of the compositeness scale.) For branching ratios and other quantities involving leptons, one needs to know $g_{new,l}$. One can, for instance, choose the range of $g_{new,l}$ so as to fit $R \equiv \Gamma(had)/\Gamma(l\bar{l})$ and predict what other quantities such as Γ_Z, A_{LR}, and σ_{had} might be. This is the procedure that we shall follow below. As we shall see, it turns out that the range of parameters that fits R will predict A_{LR} to be consistent with the SLD data rather than the corresponding LEP data.

We list in Table 3 the predicted values for R, A_{LR}, Γ_Z, and σ_{had} for the range of $g_{new,l} = 0.02 - 0.035$. (The value of $\alpha_S(M_Z)$ used in this paper is 0.125.) The range for $g_{new,l}$ is chosen so as to show the correlation between R and the other quantities. Let us first notice the following behaviour. R (A_{LR}) increases (decreases) as $g_{new,l}$ decreases from 0.035 to 0.02. What happens when $g_{new,l}$ is less than 0.02? Although not listed in the table, it turns out that, for $g_{new,l} = 0.01$, the place where A_{LR} is 1σ from the the SM prediction and the LEP result, namely $A_{LR} = 0.148$ gives a value to R ($= 21 \pm 0.09$) which is at least 4σ away from the experimental value (20.788 ± 0.032). If we choose $g_{new,l} \gtrsim 0.02$ so that the predicted R

agrees with the experimental values, one can see from Table 3 that A_{LR} is predicted to be more in agreement with the SLD data than the LEP data. It means that our model cannot satisfy all of the LEP data. The discrepancy between the LEP and SLD data for A_{LR} might have pointed toward some kind of new physics such as the one described in this manuscript. Needless to say, it is important to resolve this discrepancy in order to be able to make any kind of statement concerning new physics in this sector.

What is the meaning of the range $g_{new,l} = 0.02 - 0.035$? Since $g_{new,q}$ is fixed by R_b, the remaining free parameter is $g_{new,l}$. But it is itself constrained by the other electroweak observables (Z width, etc...) which are basically consistent with the standard model predictions except for the SLD measurement of A_{LR}. It is precisely because of these features that the above range of $g_{new,l}$ is chosen so as to be consistent with these observables. We shall come back again to this point below.

Another observation can be made by looking at Table 3. One notices that both R and Γ_Z increase with increasing resonance mass M_V. For $M_V \geq 96$ GeV, the predicted Γ_Z will be at least 2 σ away from the fairly precise experimental value of 2.4963 ± 0.0032 GeV and this worsens as $g_{new,l}$ gets smaller.

The predictions for R, Γ_Z, A_{LR}, and σ_{had} depend on the Higgs mass, although not in a significant way. Table 3 presents predictions where m_H is taken to be 700 GeV. As we lower the Higgs mass to 100 GeV, there is an increase in these predictions by approximately 0.2 %. So these predictions are not very sensitive to the Higgs mass.

Let us now summarize our results. Table 2 lists the predictions for R_c and R_s as a function of m_t. In particular we notice the decrease in R_c. Table 3 lists the predictions for R, A_{LR}, Γ_Z and σ_{had} as a function of $g_{new,l}$, m_t and M_V. There we notice that, by fixing R to agree with the experimental values, our prediction for A_{LR} tends to agree with the SLD result. In addition, the preferred range for the new resonance mass is between 92.5 GeV and 96 GeV. Translated into $\mathcal{P}$ mass, the range is between $m_{\mathcal{P}} = 47$ GeV to $m_{\mathcal{P}} = 48.8$ GeV.

The above results, namely $M_V = 92.5 - 96$ GeV, trigger the obvious question: Is such mass range already ruled out by experiment? The answer is negative. The reasons are

twofold.

First, let us estimate the V width. Since $M_V < m_t$, V decay into five quark flavors and six lepton flavors. Its width is then given by $\Gamma_V = (1/12\pi)(15g_{new,q}^2 + 6g_{new,l}^2)M_V$. To illustrate our point, let us take $M_V = 96$ GeV and $m_t = 170$ GeV. From R_b, we extract $g_{new,q} = 0.096 - 0.163$ (the range comes from the spread in R_b). Let us take the maximum allowed value for $g_{new,l}$, namely 0.035. The V width is then estimated to be $\Gamma_V = 0.37 - 1.03$ GeV. In the LEP 1990-1991 run, the energy scan was $\sqrt{s} = M_Z \pm 3 GeV$. The 1995 run has an energy scan $\sqrt{s} = 130 - 140 GeV$. In consequence, V with a mass 96 GeV would not have been seen *directly*. In fact one can safely say that $M_V = 94.5 - 96$ GeV would be outside the range of direct detection. The lower mass range, 92.5 GeV - 94.5 GeV, is more problematic although it is possible that one might miss such V in that mass range. In any case, at least the range 94.5 GeV - 96 GeV does not appear to be ruled by the present energy scan.

The second point concerns the upper bound of 96 GeV. This value is by no means a firm prediction. It depends on a number of things: the experimental spread of the electroweak observables, the spread in α_S, etc...This upper bound could easily be higher than 96 GeV by a few GeV. An extensive analysis will be carried out in a forthcoming article.

As far as direct detection is concerned, the model is well and alive. We would like to suggest a LEP scan of 100 GeV down to M_Z. It will be a crucial test of this model.

Have we or have we not seen V indirectly through electroweak observables away from the V resonance? The most obvious places to look at are the Z width and σ_{had}. As we have discussed above and as shown in Table 3, as long as $g_{new,l} = 0.02 - 0.035$, our numbers for these quantities agree with the experimental numbers, which themselves are consistent with the Standard Model. So by just looking at Γ_Z and σ_{had}, one *cannot* tell whether V is there or not. Since part of the motivation for building this model was to explain the *discrepancy* between the experimental results for R_b and R_c and the SM predictions, would such a discrepancy be an indirect manifestation of V? Furthermore, as we have mentioned earlier, there is a discrepancy between the SLD result for A_{LR} and that coming from LEP as well as the SM prediction. Since our result agrees with the SLD one, would that again

be an indirect manifestation of V?

To summarize, there is yet no direct nor indirect evidence against our model. On the contrary, there might already be some indirect evidence for some new phenomena of the types described here. Again an energy scan from approximately 100 GeV down to M_Z is a crucial test for our model.

Let us now turn to the other members of this *nonsequential* family, the $\mathcal{R}$ quark and the leptons $\mathcal{N}$ and $\mathcal{E}$. What constraints can one obtain on the masses of these particles? One obvious constraint is the fact that they have to be *heavier* than $M_Z/2$ since they have not yet been seen.

To be able to say more than this, one has to invoke additional information. This is where the S and T parameters [11], or the ϵ parameters of [3], come in. To be able to use these parameters in our context, one has to have an effective $SU(2)_L \otimes U(1)_Y$ theory. This is possible if the extra Z' mixes very little with the SM Z. At the beginning of the section on the phenomenological analysis of $Z \to b\bar{b}$, we have discussed this possibility and we have referred to an analysis done by Ref. [3,4] concerning electroweak precision constraints on extended gauge models such as the one considered here. There it was found that the mixing angle between Z and Z' is constrained to be less than 1 [3], an explicit contribution of Z' to the ϵ parameters was given. It can be seen there that this contribution is negligibly small for very small mixing and one is practically back to the SM analysis. We refer the reader to Ref. [3,4] for more details. In consequence, we shall *assume* in this paper that this mixing, which depends on the details of the Higgs sector, is negligible (less than at most 1 %) and its effects on electroweak precision measurements such as the oblique parameters S and T can be neglected. In consequence, one has practically an effective $SU(2)_L \otimes U(1)_Y$ theory. We can then make use of the most up-to-date determination of S and T to constrain the masses of $\mathcal{R}$, $\mathcal{N}$, and $\mathcal{E}$.

Before carrying out this analysis, a useful remark is in order here. Since this new family is *nonsequential*, there is no reason to expect the masses and mass splitting (between up and down members) to be "similar" in pattern to the other three families.

We use the most recent determination of the new physics contribution to S and T as fitted by Ref. [1]. They are:

$$S_{new} = -0.28 \pm 0.19 \; {}^{-0.08}_{+0.17}, \tag{19a}$$

$$T_{new} = -0.20 \pm 0.26 \; {}^{+0.17}_{-0.12} . \tag{19b}$$

.

We shall use $S_{new}^{max} = 0.08$ and $T_{new}^{max} = 0.23$.

To compute S_{new} and T_{new} in our model, we need, in addition to the range for $m_{\mathcal{P}}$ quoted above, one more input: the mass of one lepton which we shall choose to be the mass of the heavy neutrino. Since this is not meant to be an exhaustive discussion, we shall restrict ourselves to a neutrino mass of 46 GeV (other starting values will be included in a more comprehensive analysis). We shall assume that the neutrino, $\mathcal{N}$, is a Majorana particle. The contribution of the leptons to S and T can now easily be computed [12].

As mentioned above, we now require (from $S_{new}^{max} = 0.08$ and $T_{new}^{max} = 0.23$)

$$S_{new}^{q} + S_{new}^{l} \leq 0.08, \tag{20a}$$

$$T_{new}^{q} + T_{new}^{l} \leq 0.23. \tag{20b}$$

For a given $m_{\mathcal{P}}$ and $m_{\mathcal{N}}$, we compute S and T for a range of $m_{\mathcal{R}}$ and $m_{\mathcal{E}}$, keeping in mind the above constraint. We now list the relevant values, all of them computed with $m_{\mathcal{N}} = 46$ GeV.

For $m_{\mathcal{P}} = 47$ GeV, we have: 1) $S_{new}^{q} = 0.122$, $S_{new}^{l} = -0.042$, $T_{new}^{q} = 0.022$, $T_{new}^{l} = 0.208$ corresponding to $m_{\mathcal{R}} = 67$ GeV and $m_{\mathcal{E}} = 162$ GeV; 2) $S_{new}^{q} = 0.072$, $S_{new}^{l} = 0.008$, $T_{new}^{q} = 0.195$, $T_{new}^{l} = 0.035$ corresponding to $m_{\mathcal{R}} = 107$ GeV and $m_{\mathcal{E}} = 97$ GeV. Notice that as $m_{\mathcal{R}}$ increases, $m_{\mathcal{E}}$ decreases. The allowed ranges for $m_{\mathcal{R}}$ and $m_{\mathcal{E}}$ are therefore $67 GeV \leq m_{\mathcal{R}} \leq 107 GeV$ and $162 GeV \geq m_{\mathcal{E}} \geq 97 GeV$. Any other value outside that range is incompatible with the constraint.

For $m_{\mathcal{P}} = 48.8$ GeV, we have: 1) $S^q_{new} = 0.122$, $S^l_{new} = -0.042$, $T^q_{new} = 0.023$, $T^l_{new} = 0.207$ corresponding to $m_{\mathcal{R}} = 69$ GeV and $m_{\mathcal{E}} = 162$ GeV; 2) $S^q_{new} = 0.078$, $S^l_{new} = 0.002$, $T^q_{new} = 0.172$, $T^l_{new} = 0.058$ corresponding to $m_{\mathcal{R}} = 105$ GeV and $m_{\mathcal{E}} = 110$ GeV. The allowed ranges are $69 GeV \leq m_{\mathcal{R}} \leq 105 GeV$ and $162 GeV \geq m_{\mathcal{E}} \geq 110 GeV$.

Again the above results refer to $m_{\mathcal{N}} = 46 GeV$. For $m_{\mathcal{N}} = 48 GeV$, the ranges are slightly modified (the lower bounds are slightly higher). A more comprehensive analysis for various values of $m_{\mathcal{N}}$ will be presented elsewhere.

What are the implications of the above constraints on $m_{\mathcal{R}}$ and $m_{\mathcal{E}}$ coming from S and T?

First, $m_{\mathcal{E}}$ has to be at least 97 GeV, and most likely at least 110 GeV. Therefore $\mathcal{E}$ is not likely to be found at LEP2. What could be found at LEP2 would be at least *one* new threshold, the $\mathcal{P}$ quark, and possibly two, the $\mathcal{R}$ quark, if it is light enough. What we mean by new threshold here is simply the appearance of the first resonance (lowest lying $Q\bar{Q}$ state). It would be an experimental challenge to find the nonsequential charged lepton with mass greater than 97 or 110 GeV at hadron colliders. One interesting scenario is when both quarks might be found at LEP2, e.g. when $m_{\mathcal{P}} = 49$ GeV, $m_{\mathcal{R}} = 81$ GeV. The constraint from S and T would imply that that $m_{\mathcal{E}} \sim 136$ GeV. How would one detect such a heavy nonsequential charged lepton?

As alluded to in the beginning of the paper, this new family naturally involves new physics which can give rise to non-standard decays of the $\mathcal{R}$ quark and consequently invalidates the CDF and D0 limits of 118 GeV and 131 GeV. In such a case, the lower limit on the $\mathcal{R}$ quark would be 62 GeV. Our own lower limits on the $\mathcal{R}$ quark mass are higher than that value. Now, from Eq. (3) it follows that if $g^2_B/\Lambda^2 \geq g^2/2M^2_W$, where g is the weak coupling, the leptonic decay of $\mathcal{R}$ would be mostly into $\mathcal{P}\tau\nu$. Below we shall see if it is reasonable to have such a constraint. This opens up the possibility that the whole new quark family can be found by LEP2. First the R ratio would be 16/3 or at least $12/3 = 4$ (if the $\mathcal{R}$ quark mass is above 81 GeV). Some words of caution are in order. The last number depends of course on being able to detect the $\mathcal{P}$ quark which could conceivably escape the detector

because of its possible relatively "long" lifetime. In that case, the R ratio would probably be unchanged, namely 11/3, i.e. one would not see the $\mathcal{P}$ quark even if one were above its open threshold. The 1995 run of LEP1.5 with a center of mass energy well above the open $\mathcal{P}$ threshold, did not show any increase in the R ratio. It implies that the $\mathcal{P}$ lifetime should be long enough for it to escape the detector. This is conceivable in our scenario since $\mathcal{P}$ is a *nonsequential* quark with little mixing to the other three families and, consequently, could have a long lifetime. In some sense, the LEP1.5 result puts a constraint on the minimum lifetime $\mathcal{P}$ could have. In fact, one can put a rough limit on the mixing of $\mathcal{P}$ with the other quarks using the LEP1.5 constraint. One can compute the mean decay length of $\mathcal{P}$ (see e.g. [7] on p. 76) taking $\sqrt{s} = 130$ GeV, $m_{\mathcal{P}} = 47$ GeV. Requiring the decay length to be approximately greater than say 10 m, one finds that $\|V\|^2 = \|V_{Pc}\|^2 + \|V_{Pu}\|^2$ should be less than 3×10^{-13} giving $\|V\| \leq 5 \times 10^{-7}$. Needless to say, this is only a rough limit. Incidentally, this limit is consistent with the cosmologically comment made below. The $\mathcal{P}$ quark can form neutral and charged mesons with the light quarks. One might wonder if the charged mesons might not leave some tracks in the detector. This is an experimental issue which needs to be carefully examined to see if these kinds of tracks might have been missed. If $\mathcal{R}$ is light enough (below 80 GeV), it could be produced at LEP2 but its identification might be tricky since its main decay is $\mathcal{R} \to \mathcal{P} f \bar{f}$, where f is a standard light fermion, and $\mathcal{P}$ can escape the detector. In any case, it would be interesting to watch out for unusual events related to the one just mentioned. If $\mathcal{R}$ is heavier than 81 GeV then one would not see any increase in the R ratio even at LEP2 since there was none at LEP1.5. In this case the direct detection of this new, nonsequential family of quarks will have to rely on hadron machines.

As we have emphasized earlier, by *nonsequential* we really mean that there is very little mixing of this new family with the other three. This tiny mixing would be enough to evade cosmological constraints on stable quarks [13]. Even with a mixing as small as, e.g. λ^{10} between $\mathcal{P}$ and the charmed quark, the $\mathcal{P}$ lifetime would be of the order 10^{-8} sec which is certainly fast enough to evade any of such constraint.

Finally we would like to say a few words about the scales of "compositeness" in our model.

A four-fermi coupling as given by $\mathcal{L}_{q0}$ would be diagramatically similar to a quark diagram for meson-meson scattering except that here we would have a scalar line instead of one of the two quark lines. It follows that $g_{new,q}$ is not necessarily given by the wave function at the origin. We shall *assume*, for the sake of estimate, that we can write

$$g_{new,q} \equiv (g_q^2/\Lambda^2)g_H^2 F_V, \tag{21}$$

where g_H^2 represents the rescattering of the scalar components. If $g_q^2/4\pi = g_H^2/4\pi = 2.5$, Λ can be computed in terms of R_b using the definition of $g_{new,q}$ discussed above. Under the above dynamical assumption, the values for Λ are listed in Table 5. The range of Λ for each value of M_V corresponds to R_b^{max} and R_b^{min}. Notice that these values can easily be underestimated by a factor of two or so. The point is that they do not have to be as high as 10 or 100 TeV. In summary the scale of "compositeness" in our model can be as low as a few TeVs. Caution should be applied to the literal interpretation of Λ as the "compositeness" scale which, in general, might not be too different from Λ itself.

Are these estimates consistent with experiment? Is there any "evidence" for compositeness? We shall briefly address these questions below.

One word of caution is in order here. Present experiments probing compositeness only deal with operators of the type represented in Eq. (4) which involve only fermions of the first three generations. As we have stated above, the coefficients g_i^2/Λ_i^2 are not necessarily identical to g_q^2/Λ^2. The CDF limit on quark "compositeness" based on dijet invariant mass spectrum set a limit of $\Lambda_i \geq 1.4 TeV$ for $g_i^2 = 4\pi$. (This is also consistent with the TRISTAN limit.) There is some indication that the CDF high p_T data shows some discrepancy with the QCD prediction. Much work needs to be done in order to clarify both the experimental situation and the QCD prediction (gluon distribution, etc...), but there is a possibility that it is a signal for quark compositeness with a "low" compositeness scale. We shall see in the not-too-distant future whether this possibility is true or not. *Even if* we assume that the

above coefficients are similar then, taking into account the uncertainty in extracting Λ from $g_{new,q}$ described above, we can safely say that our crude estimate is not inconsistent with the experimental lower bound. Needless to say, much more detailed studies are needed to lay out the various constraints on dynamical assumptions coming from experiment. Some of these issues will be dealt with in a subsequent work.

If g_B^2/Λ_B^2 as written in Eq. (3) were similar to g_q^2/Λ^2 then the characteristic strength would be approximately $2 \cdot 10^{-5}\ GeV^{-2}$. This is to be compared with a characteristic weak interaction strength $g^2/2M_W^2$ at the $\mathcal{R}$ mass which is approximately $3 \cdot 10^{-5}\ GeV^{-2}$. Even with the above assumption, one can see that the leptonic decay of $\mathcal{R}$ will be mainly in the channel $\mathcal{P}\tau\nu$. Relaxing that assumption can make this mode even stronger if g_B^2/Λ_B^2 is given a larger value. The CDF and D0 limits of 118 GeV and 131 GeV assuming standard decay will no longer be applicable. The lower limit of 62 GeV will then be applicable. This is consistent with our lower bound of approximately 67 GeV on the mass of $\mathcal{R}$.

IV. CONCLUSION

We have presented a simple scenario to explain the "anomaly" in R_b and, as a consequence, we have made a number of predictions, R_c, etc..., including the presence of a new, *non- sequential* fourth family, some of whose members could have masses below M_W, an exciting prospect for near-future discoveries. In particular, a charge -1/3 quark is predicted to lie between 47 and 49 GeV. Its charge +2/3 companion is constrained to lie above 67 GeV and, as a consequence, it is possible to have two (but *at least* one) new thresholds below M_W. An energy scan from 100 GeV down to M_Z would provide a crucial test of this model. With the constraint that the nonsequential neutrino be heavier than $M_Z/2$, the nonsequential charged lepton turned out to be heavier than 97 GeV. These predictions are firm and the model can be easily disproved if none of these particles are found within the capability of LEP2. Since this is a composite model, we have estimated the "compositeness" scale to be "low", i.e. below approximately 5 TeV. This is relevant to a suggestion (to be

confirmed) that signals of "compositeness" might have been seen at CDF.

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TABLES

TABLE I. The Standard Model predictions for $R_f^{SM} \equiv \Gamma(Z \to f\bar{f})/\Gamma(had)$ as functions of the Higgs boson and top quark masses. Here $R_e^{SM} \equiv \Gamma(had)/\Gamma(e\bar{e})$

$m_H(GeV)$	$m_t(GeV)$	R_b^{SM}	R_c^{SM}	R_s^{SM}	R_u^{SM}	R_e^{SM}
100	150	0.2162	0.172	0.2199	0.172	20.7818
100	160	0.21586	0.172	0.22	0.172	20.779
100	170	0.2155	0.1722	0.22	0.1722	20.776
100	190	0.21473	0.1724	0.22	0.1725	20.769
700	150	0.2162	0.172	0.22	0.172	20.763
700	160	0.2159	0.172	0.22	0.172	20.76
700	170	0.21554	0.1721	0.22	0.1721	20.758
700	190	0.21477	0.1723	0.22	0.1724	20.752

TABLE II. Predictions for the ratios $R_c = R_u$, $R_s = R_d$, as functions of m_t

$m_t(GeV)$	R_c	R_s	R_c^{exp}
150	0.1634 ∓ 0.0026	0.2258 ± 0.0017	0.1540 ± 0.0074
160	0.1629 ∓ 0.0026	0.2261 ± 0.0017	0.1540 ± 0.0074
170	0.1624 ∓ 0.0026	0.2265 ± 0.0017	0.1540 ± 0.0074
190	0.1615 ∓ 0.0026	0.2273 ± 0.0017	0.1540 ± 0.0074

TABLE III. Predictions for $R \equiv \Gamma(had)/\Gamma(l\bar{l})$, A_{LR}, Γ_Z, and σ_{had} as functions of M_V, m_t and $g_{new,l}$. They are to be compared with the following experimental values: $R = 20.788 \pm 0.032$, $A_{LR}(SLD) = 0.1551 \pm 0.004$, $A_{LR}(LEP) = 0.139 \pm 0.0089$, $\Gamma_Z(GeV) = 2.4963 \pm 0.032$, and $\sigma_{had}(nb) = 41.488 \pm 0.078$. The two values for each prediction correspond to $g_{new,l} = 0.02, 0.035$ respectively.

M_V, m_t(GeV)	R	A_{LR}	$\Gamma_Z(GeV)$	$\sigma_{had}(nb)$
92.5,150	$(20.8,20.6) \pm 0.09$,	0.155,0.162	$(2.507,2.502) \pm 0.008$	$(41.91,42.45) \pm 0.44$
92.5,160	$(20.817,20.623) \pm 0.09$	0.155,0.162	$(2.511,2.508) \pm 0.008$	$(41.9,42.44) \pm 0.44$
92.5,170	$(20.833,20.64) \pm 0.09$	0.155,0.162	$(2.516,2.512) \pm 0.008$	$(41.88,42.42) \pm 0.44$
92.5,190	$(20.87,20.67) \pm 0.09$	0.155,0.162	$(2.527,2.522) \pm 0.008$	$(41.86,42.4) \pm 0.44$
94,150	$(20.867,20.72) \pm 0.09$,	0.153,0.158	$(2.508,2.505) \pm 0.008$	$(41.74,42.14) \pm 0.44$
94,160	$(20.88,20.733) \pm 0.09$	0.153,0.158	$(2.511,2.508) \pm 0.008$	$(41.9,42.44) \pm 0.44$
94,170	$(20.9,20.8) \pm 0.09$	0.153,0.158	$(2.518,2.514) \pm 0.008$	$(41.71,42.12) \pm 0.44$
94,190	$(20.93,20.78) \pm 0.09$	0.153,0.158	$(2.528,2.525) \pm 0.008$	$(41.68,42.1) \pm 0.44$
96,150	$(20.93,20.83) \pm 0.09$,	0.15,0.153	$(2.51,2.508) \pm 0.008$	$(41.56,41.83) \pm 0.44$
96,160	$(20.95,20.85) \pm 0.09$	0.15,0.153	$(2.514,2.512) \pm 0.008$	$(41.55,41.82) \pm 0.44$
96,170	$(20.96,20.86) \pm 0.09$	0.15,0.153	$(2.52,2.517) \pm 0.008$	$(41.54,41.8) \pm 0.44$
96,190	$(21.,20.9) \pm 0.09$	0.15,0.153	$(2.53,2.527) \pm 0.008$	$(41.51,41.78) \pm 0.44$

TABLE IV. The values of the "compositeness" scale Λ as a function of M_V= 92.5-96 GeV and m_t= 150-190 GeV. The spread reflects the error in R_b.

Λ(TeV)	150	160	170	190
92.5	1.9-2.51	1.87-2.42	1.83-2.34	1.76-2.17
94	1.64-2.2	1.61-2.12	1.58-2.04	1.51-1.89
96	1.36-1.83	1.33-1.76	1.3-1.7	1.24-1.57